Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia - Social and Behavioral Sciences 53 (2012) 266 – 275

Procedia
Social and Behavioral Sciences

SIIV - 5th International Congress - Sustainability of Road Infrastructures

Effect of different production conditions on the quality of hot recycled asphalt mixtures

Joel R.M. Oliveira[a]*, Hugo M.R.D. Silva[a], Liliana P.F. Abreu[b], Paulo A.A. Pereira[a]

[a]*Territory, Environment and Construction Centre, Department of Civil Engineering, University of Minho, Campus de Azurem, 4800-058 Guimarães, Portugal*

[b]*Department of Civil Engineering, University of Minho, Campus de Azurem, 4800-058 Guimarães, Portugal*

Abstract

This paper focuses on the study of the influence of different RAP preparation procedures, prior to the production of a recycled asphalt mixture, on the success of the manufacturing process. A 50% recycling ratio was used in order to test if a high level of RAP incorporation could be achieved by an adequate control of the production process. It was concluded that when an adequate size reduction and separation procedure is used, mixtures with better quality can be obtained since the mix design specifications can be achieved more easily and the binder of the final mixture is less aged by the high temperatures.

Keywords: Asphalt recycling; production conditions; RAP separation; quality control; aging.

1. Introduction

The recycling of asphalt pavements is a production process with environmental and economic benefits that can be seen as a sustainable option for the paving industry. The use of high Reclaimed Asphalt Pavement (RAP) ratios in asphalt mixtures prevents the disposal of the RAP material in landfills, while reduces the amount of new resources used (aggregates and bitumen), thus being an effective technology at environmental and energy levels.

In most countries the total amount of reclaimed asphalt and the production of recycled asphalt continue to grow regularly, as well as the percentage of RAP used in recycled mixtures [1]. Several studies [2-5] have been carried out in the past with up to 60% content of recycled asphalt, and this amount is mainly limited by practical issues related to the production of the mixtures in the asphalt plant. In fact, when studying recycled mixtures in laboratory it can be feasible to use the total recycling technology (which reuses 100% RAP) with an adequate

* Corresponding author. Tel.: +351-253510200; fax: +351-253510217.
E-mail address: joliveira@civil.uminho.pt

 doi:10.1016/j.sbspro.2012.09.879

performance, provided that an adequate control of the production conditions is guaranteed [6].

In the production of hot recycled asphalt, it is necessary to overheat the virgin aggregates in order to provide indirect heat to the RAP. This imposes limitations on the amount of RAP that can be added, which are related to productivity issues. The limit is around 50% for the production of hot recycled asphalts in conventional batch plants (maximum capacity of heat and gaseous emissions limits), while drum-mix asphalt plants can process up to 60-70% of RAP, with a practical limit of 50% due to emissions [7]. Some modifications have been introduced to conventional asphalt plants in order to increase the productivity and reduce aging of the old binder during mix production. This includes counterflow drum mixer, microwave heaters [8] and the separation of RAP in different fractions [9] for better quality control of the gradation and selective heating of the RAP material.

The success of the asphalt recycling technology with high amounts of RAP is not yet seen among the scientific community as a full achievement, because it is still quite sensitive to the quality of RAP (origin, variability, stocking) and the production conditions, namely the strict control of temperatures and aggregate gradation [5, 10].

Regarding the influence of using high amounts of RAP on the performance of the resulting recycled mixtures, in general, the rutting resistance and the stiffness of the mixtures increase with an increase in the RAP content and, usually, the increase in stiffness reduces the fatigue resistance of the mixture [5, 11]. However, other authors [12] concluded that the aged binder in RAP formed a stiffer layer coating the RAP aggregate particles, and his layered system helped to reduce the stress concentration within the HMAs and the aged binder mastic layer was actually serving as a cushion layer in between the hard aggregate and the soft binder mastic. This may explain the improved fatigue resistance of mixes containing RAP, also reported in other laboratory studies [6]. Another study [13] with recycled HMA in airport pavements concluded that recycled HMA containing 40% RAP exhibited similar and even better performance than control HMA without RAP, except for the moisture susceptibility, while the incorporation of 70% RAP has shown some fatigue problems.

The main objective of the current research paper was to study the influence of using different RAP preparation procedures, including separation and disaggregation methods, on the success of the final product obtained during the production of a recycled asphalt mixture (namely to fulfill the mixtures' specifications for gradation and binder content). The study was carried out in the laboratory, in order to test the whole production process and to encourage its application in pavements.

The laboratory study comprised the evaluation of the separation of the RAP material into coarse and fine fractions in order to use different heating procedures. The coarse RAP material was heated together with the virgin aggregates while the fine RAP material was incorporated into the mixture at room temperature, in order to reduce the asphalt binder aging. Different separating processes and sieve dimensions were assessed and their influence on the amount of coarse and fine RAP fractions obtained was evaluated, taking into consideration the need to fulfill the gradation specifications of the recycled mixture. In this study, a 50% recycling ratio was used in order to test if a high level of RAP incorporation could be achieved by using an adequate control of the production process, namely those previously referred. Finally, the durability of the recycled mixtures prepared with the different separation methods was also evaluated through the use of water sensitivity tests.

2. Materials and methods

2.1. Materials used in the study

One of the objectives of this study was to assess the viability of using a high recycling rate (50%) in the production of new bituminous mixtures, by using an adequate control of the production process and without compromising the performance of the mixture. In the present study, half of the recycled mixtures produced were constituted by reclaimed asphalt pavement (RAP) material. The remaining half of the recycled HMAs was constituted by new virgin aggregates and bitumens, especially chosen to rectify the grading of the RAP aggregates (usually with an excess of fines) and the hard penetration grade of the RAP aged bitumen.

2.1.1. Reclaimed asphalt pavement (RAP) material

The RAP used in this study was obtained from a Motorway pavement in Portugal, by milling the thickness of the pavement corresponding to one layer only (surface course) in order to assure that the material would be homogeneous. The pavement with 15 years in service was presenting fatigue cracking, thus being expected that the RAP binder would be very hard after being exposed to long term aging.

2.1.2. Virgin aggregates and bitumen

All virgin aggregates used in this study are granite igneous rocks, while the filler is limestone. The choice of the aggregate type for this study was imposed by the aggregate availability on the region where the study was carried out. Taking into consideration that the RAP material usually have an excess of fines [6], the virgin aggregates used should be composed by approximately 40% of coarse material (6/14) and only 10% of fines (4/6, 0/4 and filler). These percentages were adjusted with a finer tune for each mixture studied in order to fit the grading envelopes defined in the Portuguese specifications.

The new virgin bitumen used was a 40/60 pen grade bitumen, because the majority of the conventional bitumens used in Portugal have penetration grades between 35 and 70 (□0.1 mm). This bitumen was characterized through penetration (EN 1426), softening point (EN 1427) and dynamic viscosity (EN 13302) tests. The dynamic viscosity tests were performed at a range of high temperatures (110-180 ºC), in order to study the mixing/compaction conditions, using a rotating spindle apparatus, according to a predefined procedure [14].

2.2. RAP characterization

2.2.1. Separation into different RAP fractions

In order to determine the influence of different strategies of handling RAP prior to the production of recycled asphalt mixtures, three different separation procedures were used in the present study. Thus, the first option (Procedure A) was to disaggregate the RAP particles that result from the milling operations on site, using a laboratory mixer (after warming the RAP up to 100 ºC), and separating it into two fractions using a sieve of 8 mm aperture (after it cooled down); the second option (Procedure B) was to simply separate the RAP on the 10 mm sieve; the third and last option (Procedure C) was to separate the RAP in the 8 mm sieve.

The objective of separating the RAP into coarse and fine fractions was to use different heating temperatures for each fraction in the production of the recycled mixtures. In order to avoid an excessive binder aging effect during the production process, the fine fraction of the RAP would be added to the mixture at ambient temperature (in this case around 25 ºC), while the coarse fraction would be heated (up to 200 ºC) together with the new aggregate that would be added to the mixture, in order to obtain an adequate mixing and compacting temperature according to the type of new binder used.

2.2.2. Binder content

The percentage of bitumen on the different fractions of RAP was obtained by the ignition method (EN 12697-39). Different samples of each fraction were tested and the results showed low variation, which confirmed a good homogeneity of the different RAP fractions. These results were essential to define the quantity of new bitumen to add during the mix design, and to evaluate the efficiency of the RAP separation method (a good separation should result in high binder content of the fine RAP fraction and low binder content of the coarse RAP fraction).

2.2.3. Particle size distribution

The different fractions of RAP material were incinerated, according to the EN 12697-39, in order to burn the bitumen and to evaluate the grading of the aggregates of those fractions of RAP, according to the EN 12697-2. The particle size distribution of the RAP fractions was also used to determine the new aggregates to be used in the mix design in order to fit within the grading envelope of a conventional surface course mixture.

2.2.4. Binder recovery and characterization

In order to characterize the aged binder of RAP, it was separated from the RAP sample by dissolving it in toluene and, after removing all solid particles from the bitumen solution (using filter and tube centrifuge), the bitumen was recovered by vacuum distillation using a rotary evaporator, in accordance to the EN 12697-3 standard. Later, the recovered bitumen was characterized through penetration (EN 1426), softening point (EN 1427) and dynamic viscosity (EN 13302) tests (the last type of test was performed at a range of temperatures).

2.3. Recycled HMA mix design

The best composition for the recycled HMA mixture was obtained by means of using the empirical Marshall mix design method, as defined in the Portuguese specifications and in the EN 13108-1 standard. Although three different recycled mixtures produced with particular RAP preparation methods have been studied this work, the mix design was carried out only for the mixture using the procedure A of RAP separation (the most laborious and rigorous method). The binder content obtained for this mixture was maintained for all recycled HMAs in order to reduce the number of extraneous variables during the comparison of the different mixtures.

2.3.1. Aggregate specifications

Given that the empirical specifications are based on compositional recipes, the grading limits have to be strict and must be totally fulfilled, in order to enable the use of the mixtures in road pavements without premature distresses. Thus, the design grading curve of an AC surf/bin 14 was set for the recycled HMAs in order to meet the present Portuguese specifications [15]. This gradation was selected because it can be used both in surface and binder courses, and because it is easier to adjust this type of gradation to mixtures with high contents of RAP.

2.3.2. Optimum binder content

In order to design the recycled AC surf/bin 14 mixtures and to evaluate their mechanical properties designated on the empirical specifications, five batches of mixture were prepared by using different percentages of bitumen in intervals of 0.5% between 4.0% and 6.0%. For this mixture, the new aggregates, the coarse RAP and the filler were batched and put in an oven at 200 ºC, while the fine RAP was not heated and the new bitumen was heated at 150 ºC. In order to achieve an adequate workability, the hot aggregates were introduced in the mixer together with the fine RAP fraction and mixed for 2 minutes, after which the new binder was added. After the mixing process, three specimens were compacted with 75 blows per face (EN 12697-30) for each percentage of bitumen and their apparent density was evaluated. The theoretical maximum density (TMD) of all the mixing batches was also assessed. The main volumetric characteristics (voids content and VMA) were calculated based on the results of these two tests and on the binder content of the mixtures. Finally, all the specimens were tested by using the Marshall test procedures (EN 12697-34), registering the load (stability) and deformation (Marshall flow) values.

According to the EN 13108-1 standard, the optimum binder content of the Marshall mix design method is the average value of the binder contents resulting from the maximum Marshall stability (EN 12697-34), air voids content equal to 4% (for this AC surf/bin 14 mixture) and maximum bulk density.

2.4. Recycled mixture characterization and performance

After concluding the mix design of the recycled mixtures, it was possible to define the binder content and the final gradation of the mixtures. Then, three mixtures were produced using different RAP preparation methods:

- Mixture 1: 50% RAP (disaggregated and separated in #8mm) + 50% new aggregates and bitumen 40/60;
- Mixture 2: 50% RAP (separated in #10mm) + 50% new aggregates and bitumen 40/60;
- Mixture 3: 50% RAP (without separation) + 50% new aggregates and bitumen 40/60.

Mixtures 1 and 2 correspond, respectively, to the procedures A and B used for RAP separation, while mixture 3 was defined to analyze the properties of a recycled HMA without separation (in contrast to mixtures 1 and 2). Thus, the procedure C of separation was not used to produce any mixture studied in this part of the work.

The percentages of fine and coarse fractions of RAP material were defined in order to maximize the use of RAP after separation. The concern of minimizing the binder aging by introducing the maximum quantity of fine RAP material at room temperature was also taken into consideration, but in order to maintain a good productivity level in an asphalt plant, the quantity of fine RAP material introduced at ambient temperature shall be limited to 30% [16]. Thus, mixtures 1 and 2 used 30% of fine and 20% of coarse RAP material.

The production temperatures used to heat the RAP and the new aggregates of mixtures 1 and 2 were those previously presented, i.e., the fine fraction of RAP was introduced at room temperature (25 ºC), while the coarse fraction of RAP and the new aggregates were introduced at 200 ºC. The RAP material used in mixture 3 was not separated in order to observe the consequences of heating the whole RAP together with the new aggregates, at 150 ºC, in order to obtain a mixture temperature similar to that of Mixtures 1 and 2.

The characterization of the studied mixtures, presented in the following sections of the paper, was carried out in order to control the quality of the mixtures obtained using each mentioned production procedure, and to assess their mechanical performance through simple testing.

2.4.1. Evaluation of mixtures composition for quality control

The evaluation of the composition of the recycled mixtures was carried out as quality control method, in order to assess which one of the different production conditions resulted in mixtures with a particle size distribution, binder content and air voids content near to the target ones defined during the mix design.

The particle size distribution of the different recycled mixtures was obtained after incineration, according to the EN 12697-39 standard, in order to burn the bitumen and to evaluate the grading of the aggregates comprised in those mixtures, according to the EN 12697-2 standard. The binder content of the different recycled mixtures was obtained by the ignition method (EN 12697-39).

The air voids content of the specimens, compacted with 75 blows on each face (EN 12697-30), is an important information to evaluate compactability of the mixtures, and was calculated based on the results of their apparent density (EN 12697-30) and on the theoretical maximum density (EN 12697-30) of all the mixing batches.

2.4.2. Water sensitivity

The evaluation of the water sensitivity is determined in Europe by the EN 12697-12. According to this standard, two groups of three specimens are tested for the indirect tensile strength (ITS) after a different conditioning period. In that period, one group is kept dry and the other is immersed in water, in order to determine the influence of the water on the reduction of the strength of the mixture.

Following the determination of the ITS of each specimen, it is possible to calculate the average value of each group and the indirect tensile strength ratio (ITSR), which corresponds to the ratio between the ITS of the wet group (ITSw) and the dry group (ITSd) of specimens. The air voids content of the specimens were also assessed because they have a great influence in the water sensitivity performance of the asphalt mixtures.

2.4.3. Influence of production conditions on the properties of final binder

After the conclusion of the mixtures' performance study, the final binder present in the mixtures was characterized, in order to assess whether the different production processes would have influence on the aging of the binder. This was carried out by recovering the binder using a rotary evaporator (by vacuum distillation), in accordance to the EN 12697-3 standard (as previously described for the RAP). Then, the binder was characterized through penetration (EN 1426), softening point (EN 1427) and dynamic viscosity (EN 13302) tests. The dynamic viscosity test was carried out at various temperatures, as previously described.

The comparison between the binder properties obtained after using different production conditions can be used to select the best method that induces fewer changes to the bitumen during the most significant aging period (the mixtures production process). In fact, one of the main ideas behind the process of separation of RAP for selective heating is to reduce the bitumen aging, which can be analyzed with these results.

3. Results and discussion

The present section is divided into three main sets of results, namely, the characterization of the RAP and its constituent materials, the mix design results carried out for a mixture with 50% RAP incorporation, and the properties of three mixtures manufactured according to different production conditions.

3.1. RAP characterization

As can be observed in Table 1, different proportions were obtained between the coarse (retained in the selected sieve) and fine (passing in the selected sieve) RAP fractions for each of the adopted procedures.

Table 1. Proportion of coarse and fine RAP fractions obtained using different separation procedures (%)

Procedure	Coarse RAP	Fine RAP
A	32	68
B	39	61
C	66	34

Based on the results presented in Table 1, it is possible to conclude that procedure A is the most efficient in reducing the amount material present in the coarse fraction of the RAP. This is particularly important since the coarse RAP fraction is going to be significantly heated and if the particles are composed of an agglomeration of binder and aggregates that are retained in the selected separation sieve, a higher amount of binder will be subjected to unnecessary aging effect during the mixture production. Although procedures A and B resulted in similar results in the coarse and fine fraction proportions, it should be emphasized that the separation sieve selected for both cases is different (8mm for procedure A and 10mm for procedure B), while procedure C (where the sieve used is the same as that of procedure A) resulted in a very high proportion of coarse particles, which comprise a significant amount of agglomerated material.

In order to assess the actual gradation of the aggregate particles of each fraction, particle size distribution tests were carried out (Figure 1a) after binder ignition tests (Figure 1b) on each studied fraction.

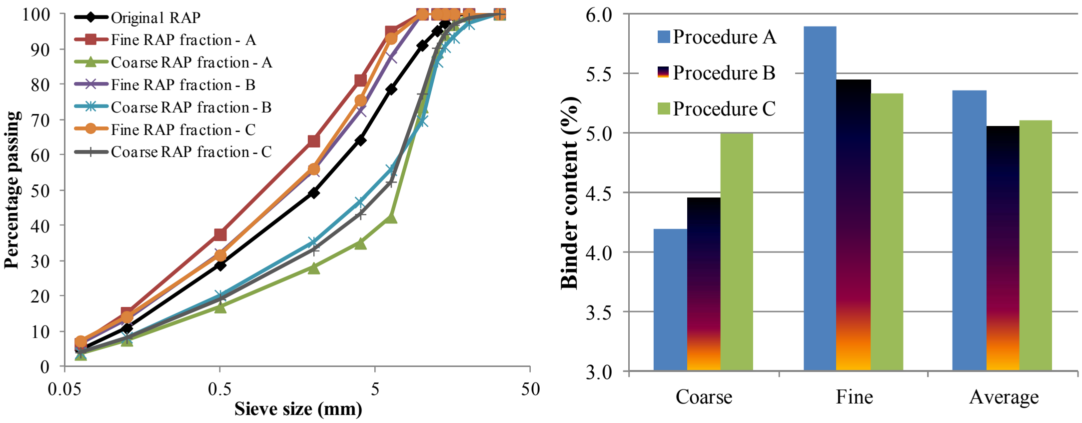

Fig. 1. (a) Particle size distribution of the RAP aggregates; (b) binder content obtained from different RAP samples

As previously mentioned, procedure A was the most efficient in separating the actual coarse and fine aggregate particles in the RAP, as can be observed in Figure 1a. Procedures B and C resulted in similar particle size distributions of each equivalent fraction, although the proportion between the fractions was different.

The samples of RAP used in this part of the study resulted in varying binder contents, as can be observed from the average values presented in Figure 1b, which highlight the existence of some variability on the composition of this type of material that may affect the homogeneity of the final product. In addition, it is possible to conclude that the amount of binder attached to the coarse particles of the RAP is significantly lower if an adequate disaggregation and separation procedure is adopted, as that of procedure A. The simple separation of the RAP into coarse and fine fractions is not so efficient and depends on the sieve size chosen. In Figure 1b, it is possible to observe that the use of the 8mm sieve in procedure C is not adequate, since it retains a significant amount of agglomerated fine particles (as presented in Table 1) with a high binder content. Based on the results obtained, it was decided to use only procedures A and B for the production of recycled mixtures, substituting the RAP obtained using procedure C by a sample of original RAP (without separation).

3.2. Recycled HMA mix design

As previously mentioned, the mix design was only carried out for mixture 1. The main results obtained are summarized in Table 2 for the aggregate gradation and in Table 3 for the Marshall mix design procedure.

Table 2. Results of the aggregate gradation of the mixture and the envelope limits

Sieve size (mm)		20	14	10	4	2	0.5	0.125	0.063
Percentage passing	Min	100	90	67	40	25	11	6	5
	Max	100	100	77	52	40	19	11	8
	Mixture	99.9	97.7	80.2	39.6	31.1	19.6	10.2	6.2

In order to meet the Portuguese specifications [15], the composition of the recycled mixture obtained comprised approximately 30% of fine RAP, 20% of coarse RAP, 38% of 6/14 agg., 5% of 4/6 agg., 4% of 0/4 agg. and 3% of filler. The optimum binder content of the studied mixture obtained from the Marshall mix design was 5.0%, which correspond to 2.4% new bitumen, since the RAP already provided 2.6% binder (1.8% in the fine and 0.8% in the coarse fractions) to the mixture.

Table 2. Results of the aggregate gradation of the mixture and the envelope limits

Binder content (%)	MTD (kg/m3)	Bulk density (kg/m3)	Voids content (%)	VMA (%)	Stability (kN)	Flow (mm)
4.0	2493	2232	10.5	19.2	15.8	3.4
4.5	2452	2249	8.3	18.1	16.6	3.5
5.0	2431	2347	3.5	14.9	17.7	3.7
5.5	2412	2334	3.3	15.7	15.0	4.6
6.0	2406	2370	1.5	15.3	15.0	4.7
Specifications [1]	-	-	3.0 – 5.0	≥ 14	≥ 7.5	2.0 – 4.0

3.3. Recycled mixtures' characterization and performance

After production of the three mixtures under study, a sample of each mixture was incinerated and the corresponding particle size distribution of the aggregate and the binder content were determined. Figure 3 shows the results of the particle size distribution of the aggregate.

As can be observed in Figure 2a, using the separation procedure A prior to produce the corresponding mixture 1, resulted in a better particle size distribution of the final mixture, since it was possible to meet the specifications more accurately. The aggregate gradation of each RAP fraction resulting from Procedure A was significantly different from the others, simplifying the aggregate fractions selection in the mix design procedure.

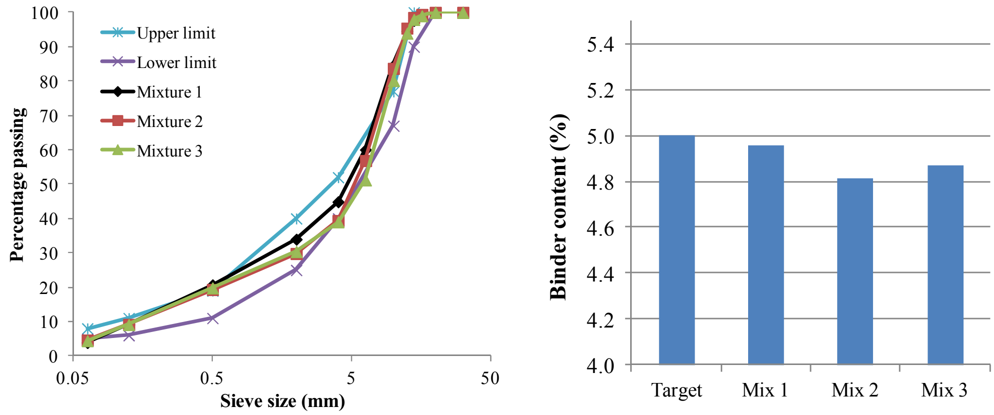

Fig. 2. (a) Particle size distribution of studied mixtures after binder incineration; (b) binder content of studied mixtures

Taking into account that some variability exists in the binder content of different RAP samples, it is expected that the binder content of asphalt mixtures incorporation 50% RAP may also present some variability, as can be observed in Figure 2b. Nevertheless, Procedure A demonstrated to be the most efficient in keeping the binder content closer to the target value, due to a better dosage control of the RAP fraction that presents a higher binder content (fine fraction).

One of the main performance related properties of asphalt mixtures is their water (moisture) sensitivity. This property was evaluated for the three mixtures under study, using indirect tensile tests. The results of each mixture are presented in Figure 3 together with the air voids content and the measured compaction temperature.

The target air voids content (4%) was achieved only for Mixture 1, which may be related to the better workability provided by a lower aging effect of the production conditions on the RAP binder, since a similar compaction temperature did not result in a similar air voids content for mixture 3. The lower compaction temperature achieved during the preparation of mixture 2 specimens may explain the higher air voids content and the corresponding lower water sensitivity test results. Also on this property, mixture 1 was that with the best performance, showing the higher ITSR values (near 85%).

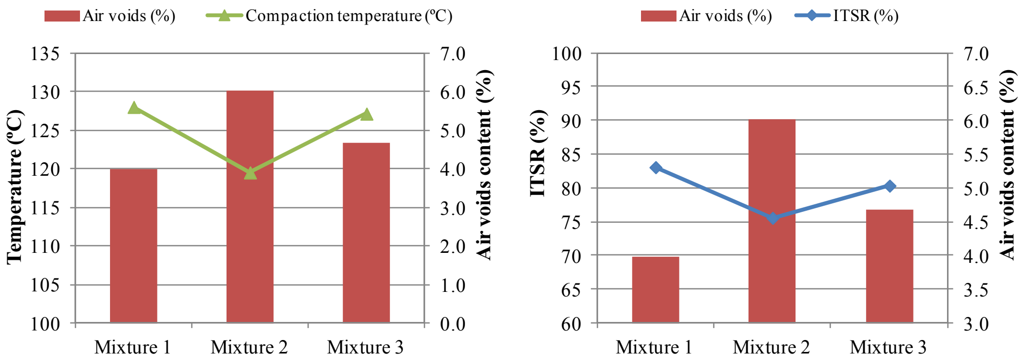

Fig. 3. Effect of the compaction temperature on the air voids content and the corresponding water sensitivity of the mixtures

In order to confirm if the good results obtained for mixture 1 could be related to the properties of the final binder present in the mixture, penetration, softening point and dynamic viscosity tests were carried out on samples of bitumen recovered from each mixture. The results are presented in Figures 4 and 5, together with the results obtained for the RAP binder and for the new 40/60 bitumen used in the preparation of all mixtures. The results presented show that some aging occurred during the production of all three mixtures, since the properties of the final binder of each mixture does not correspond to a simple average of the equivalent properties of the RAP and new binder (according to the proportions of each in the final mixture), confirming that the production stage is responsible for a considerable aging of any asphalt mixture binder. Nevertheless, it was possible to conclude that procedure A is more efficient in avoiding unnecessary aging of the RAP binder, as can be observed by the higher penetration of the binder from mixture A. In contrast, the properties of the binders recovered from mixtures 1, 2 and 3 measured at higher temperatures (i.e. softening point and dynamic viscosity) did not show significant differences due to the aging phenomenon, probably because the molecular structuring that occurs during the aging of bitumen is not so perceptible at higher temperatures, when the behavior of the bitumen is more controlled by the dispersion of those structures than by the concentration of molecules with more complex structures, i.e. asphaltenes.

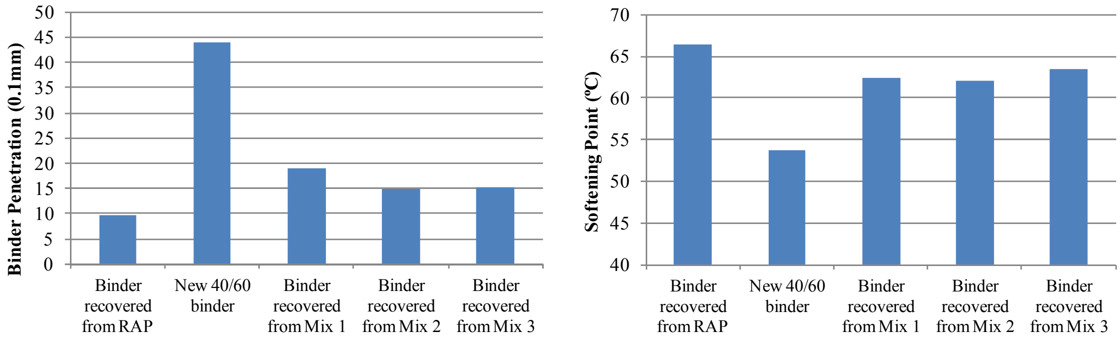

Fig. 4. Penetration and softening point of the RAP and new binders used in the recycled mixtures and of the final binders recovered from those mixtures after different production procedures

The results obtained in the present study are only related to the use of a traditional straight run bitumen as the new binder added to the recycled mixtures. As can be observed from Figure 4, the final binder of all studied mixtures is a very hard binder (10/20 pen grade bitumen), which may result in inadequate fatigue cracking performance. Thus, the incorporation of some sort of rejuvenating agent may be necessary if recycled mixtures with 50% RAP are to be produced with such type of new binder.

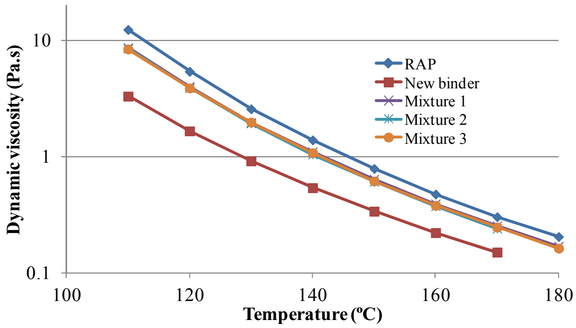

Fig. 5. Dynamic viscosity of the RAP and new binders used in the recycled mixtures and of the final binders recovered from those mixtures after different production procedures

The final bitumen recovered from mixtures 1, 2 and 3 showed dynamic viscosity results closer to the RAP binder than to the original 40/60 bitumen, even though a similar proportion of both types of bitumen were used in the mixture. This reinforces the idea that a significant part of aging occurs during the production stage. Moreover, the evolution of viscosity with the temperature is similar among the different types of binders analyzed.

4. Conclusions

The main conclusions that may be drawn from the present paper are summarized as follows:

- An adequate RAP disaggregation and separation procedure is essential to achieve the asphalt mixture specifications, namely when recipe based mix design procedures are used, if high percentages of RAP (close to 50%) are to be incorporated;
- Simple sieving separation is not an efficient procedure to separate the fine particles of RAP (with a higher binder content) from the coarse particles;
- If an efficient RAP disaggregation and separation method is used, it is possible to achieve a lower aging effect of the production procedures on the final binder of a recycled mixture;
- Water sensitivity of such mixtures is improved and may therefore result in a better in service performance, thus justifying the possible investment made in the asphalt plant to carry out the best separation method.

Acknowledgements

The authors would like to acknowledge the financial and material support given by some institutions. This work is funded by FEDER funds through the Operational Competitiveness Program – COMPETE and by National funds by FCT – Portuguese Foundation for Science and Technology in the scope of Project PTDC/ECM/119179/2010 and the Strategic Project - UI 4047 - 2011 - 2012. Thanks are also due to the Companies MonteAdriano Engenharia e Construção S.A., CEPSA and "Bezerras" Quarry (for material supply).

References

[1] PIARC (2002). Recycling of Existing Flexible Pavements. TC 8 - Flexible Roads of World Road Association (PIARC). 67 p. Paris.
[2] Celauro, C., Celauro, B. & Boscaino, G. (2010). Production of innovative, recycled and high-performance asphalt for road pavements. Resources, Conservation and Recycling, 54(6), 337-347.
[3] Pereira, P. A. A., Oliveira, J. R. M. & Picado-Santos, L. G. (2004). Mechanical characterisation of hot mix recycled materials. International Journal of Pavement Engineering, 5(4), 211-20.
[4] Oliveira, J. R. M., Silva, H. M. R. D., Abreu, L. P. F. & Gonzalez-Leon, J. A. (2012). The role of a surfactant based additive on the production of recycled warm mix asphalts – Less is more. Construction and Building Materials, 35, 693-700.
[5] Valdés, G., Pérez-Jiménez, F., Miró, R., Martínez, A. & Botella, R. (2011). Experimental study of recycled asphalt mixtures with high percentages of reclaimed asphalt pavement (RAP). Construction and Building Materials, 25(3), 1289-97.
[6] Silva, H. M. R. D., Oliveira, J. R. M. & Jesus, C. M. G. (2012). Are totally recycled hot mix asphalts a sustainable alternative for road paving? Resources, Conservation and Recycling, 60, 38-48.
[7] Hassan, R. (2009). Feasibility of Using High Rap Contents in Hot Mix Asphalt. In: AAPA (Ed). 13th International Flexible Pavements Conference. Australian Asphalt Pavement Association, Queensland, Australia.
[8] NAPA. (1996). Recycling Hot Mix Asphalt Pavements. National Asphalt Pavement Association, Lanham, MD, USA.
[9] Colbert, B. & You, Z. (2012). The determination of mechanical performance of laboratory produced hot mix asphalt mixtures using controlled RAP and virgin aggregate size fractions. Construction and Building Materials, 26(1), 655-62.
[10] Solaimanian, M. & Savory, E. (1996). Variability Analysis of Hot-Mix Asphalt Concrete Containing High Percentage of Reclaimed Asphalt Pavement. Transportation Research Record: Journal of the Transportation Research Board, 1543(1), 89-96.
[11] Rebbechi, J. & Green, M. (2005). Going green: innovations in recycling asphalt. In: AAPA (Ed.). AAPA Pavements Industry Conference. Australian Asphalt Pavement Association, Queensland, Australia.
[12] Huang, B.S., Li, G.Q., Vukosavjevic, D., Shu, X. & Egan, B.K. (2005). Laboratory investigation of mixing hot-mix asphalt with reclaimed asphalt pavement. Transportation Research Record: Journal of the Transportation Research Board, 1929, 37-45.
[13] Su, K., Hachiya, Y. & Maekawaa, R. (2009). Study on recycled asphalt concrete for use in surface course in airport pavement. Resources, Conservation and Recycling. 54(1), 37-44.
[14] Silva, H. M. R. D., Oliveira, J. R. M., Peralta, E. J. & Ferreira, C, I, G. (2009). Evaluation of the rheological behaviour of Warm Mix Asphalt (WMA) modified binders. In: Loizos, A., Partl, M. N., Scarpas, T. & Al-Qadi, I. L. (Eds.). 7th Int RILEM Symp Advanced Testing and Characterisation of Bituminous Materials (pp. 661-73). Rhodes, Greece.
[15] EP. (2011). Vol. V:03 - Pavimentação - Cap. 14.03 - Características dos Materiais. In: EP (Ed.). Caderno de Encargos Tipo Obra. Estradas de Portugal. Lisbon, Portugal (in Portuguese).
[16] Miró, R., Valdés, G., Martínez, A., Segura, P. & Rodríguez, C. (2011). Evaluation of high modulus mixture behaviour with high reclaimed asphalt pavement (RAP) percentages for sustainable road construction. Construction and Building Materials, 25(10), 3854-62.